A Point Design for a Gyrotron Traveling Wave Tube Amplifier

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The purpose of this article is to present a point design for a gyro-TWT amplifier. Steps for deriving the growth rate are explained and design results presented. Parameters for some support equipment are given and consequences of potential design parameter changes are examined.

I. Introduction

With current crowding at S- and X-bands and the greater resolution and ranging available at higher frequencies, great interest has been generated in exploring development possibilities for microwave amplifiers in the 33.5- to 35.1-GHz range for future generations of spacecraft uplinks and planetary radar. Power requirements are in the 200- to 400-kW CW range and an examination of presently available microwave tubes capable of attaining these powers at R-band frequencies has yielded little positive return. However, research and development on a new class of amplifiers that will hopefully satisfy the aforementioned needs is currently underway at many institutions throughout the world. These new amplifiers are called gyrotrons and have many advantages over the traditional microwave tubes, including the potential for using overmoded (and hence large) cavities or waveguides to minimize heat transfer problems inherent in any higher frequency scaling application. Also they are not constrained by the usual power-frequency relation, $P_{out} = \text{constant} \cdot 1/f^2$ (Ref. 1). Azimuthal phase bunching due to the dependence of the cyclotron frequency on the relativistic electron mass and magnetic coupling to RF fields in cavities and/or waveguides close to cutoff are responsible for providing the gain characteristic. Relatively high electronic efficiencies are calculated for gyrotron devices utilizing hollow cylindrical electron beams; further research and development will undoubtedly produce new advances in efficiency and output power.

At the present time, to further judge potential usefulness, it is prudent to examine gyrotron devices in view of their above-proposed uses and attempt to determine what kind of ancillary equipment, in terms of power supplies, cooling capacity, magnetic fields, etc., will be required. To do this, it is necessary to specify a particular design. Therefore, in the following sections, the mathematical starting point for the design of a gyrotron traveling wave tube amplifier is presented, and detailed results concerning bandwidth and physical dimensions are listed. It should be noted that this is a point design that is not necessarily completely optimized. Certain parameters such as maximum efficiency, for example, were assumed to be more important than bandwidth or gain per centimeter of interaction space considerations.

II. Dispersion Relation

It is necessary to derive a dispersion relationship so that wave growth rates in cylindrical coordinates can be calculated and hence efficiencies estimated. Therefore, starting with Maxwell's Equations,

$$\nabla \circ \mathbf{E} = 4\pi\rho \tag{1}$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \tag{2}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{4}$$

one obtains the following:

$$\left(\nabla_t^2 + \frac{\omega^2}{c^2} - k_z^2\right)\mathbf{E} = 4\pi i\left(\rho\mathbf{k} - \frac{\omega}{c^2}\mathbf{J}\right) \tag{5}$$

$$\left(\nabla_t^2 + \frac{\omega^2}{c^2} - k_z^2\right)\mathbf{B} = -\frac{4\pi}{c}\nabla \times \mathbf{J} \tag{6}$$

where c is the speed of light, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields in the waveguide respectively, $\mathbf{k}$ is the wave vector, ρ is the charge density, $\mathbf{J}$ is the current density, and ω is the frequency in radians. Using the TE_{01} vacuum waveguide solutions for $\mathbf{E}$ and $\mathbf{B}$ and the techniques outlined by Ott and Manheimer (Ref. 2), substitution for the current density via Vlasov Theory arguments leads to the following in the beam frame (Ref. 3):

$$\omega^2 - k_z^2 - \omega_c^2 = \frac{4\nu(1-\beta_{\|})^{1/2}}{J_0^2(x_1)} \times \left[\frac{-(\omega^2 - k_z^2)\beta_\perp^2\, Y(x_1 r_0, x_1 r_L)}{(\omega - \Omega_c)^2} + \frac{\omega Z(x_1 r_0, x_1 r_L)}{\omega - \Omega_c}\right] \tag{7}$$

$$Y(a,b) = (J_1(a)J_1'(b))^2 \tag{8}$$

$$Z(a,b) = 2Y(a,b) + bJ_1'(b)J_1''(b)\cdot(J_1^2(a)(1+a^{-2}) + (J_1'(a))^2) + 2J_1(a)J_1'(a)J_1'(b)(bJ_1'(b) - J_1(b))/ab \tag{9}$$

where $x_1 = 3.8317$, ν is a dimensionless beam density parameter, $J_{0,1}$ represents Bessel functions, r_0 is the radius of the Larmor orbit guiding center in the waveguide (see Fig. 1), r_L is the Larmor radius, ω_c is the waveguide cutoff frequency, Ω_c is the cyclotron frequency, and primes imply derivatives with respect to arguments. Frequencies, velocities, and lengths have all been normalized to c/r_w, c, and r_w, respectively, where r_w is the waveguide radius (unnormalized).

Equation (7) will yield ω_r and ω_i. The latter represents the growth rate for the amplified wave.

The electronic efficiency, η, is given by

$$\eta = \frac{\text{field energy/unit length}}{\text{injected beam energy/unit length}} = \frac{\frac{1}{8\pi}\left(\frac{\omega}{\omega_c}\right)^2 \int_{\text{AREA}} \Psi^*\Psi\, da}{N(\gamma_0 - 1)mc^2} \tag{10}$$

where Ψ is the complex field wave function and * denotes complex conjugates. N is the number of electrons/unit length, m is the mass of the electron and

$$\gamma_0 = \left(1 - \beta_\perp^2 - \beta_{\|}^2\right)^{-1/2} \tag{11}$$

and $\beta_{\|}$ and $\beta_\perp$ are the normalized parallel and perpendicular electron velocities. Bandwidths can be determined from the width of the ω_i vs k_z curve.

The beam current, beam power, and output wave power are defined respectively by the following:

$$I_b = \nu(1-\beta_{\|})^{-1/2} mc^2 \beta_{\|} \tag{12}$$

$$P_b = I_b(\gamma_0 - 1)mc^2 \tag{13}$$

$$P_w = \eta P_b \tag{14}$$

Table 1 lists results that are based on the above equations and extrapolations of curves given in Ref. 3.

III. Discussion

The amplifier (see Fig. 2) can be sized for two different total gain conditions of 40 and 50 dB, respectively. Assuming a linear growth rate over the entire length of the fast-wave structure, the whole interaction-drift space (34.90 cm in the 40-dB case and 43.63 cm in the 50-dB case) must be enclosed in the bore of a superconducting solenoid of at least the same dimension so that the hypercritical control over the strength of the axial magnetic field can be maintained to better than one percent of maximum field strength over the entire waveguide region. As can be easily seen by subtracting the output wave power from the beam power, the collector coolant assembly must be capable of dissipating 318.04 kW of continuous wave power without upsetting the cryostatic stability of the superconducting magnets (which will probably be cooled with liquid helium). Hence, the collector will be the largest and heaviest part of the amplifier just as with conventional klystron tubes. However, due to the nature of the guiding magnetic field, the "spent" electrons will impact on the collector surface in a relatively small area, possibly resulting in local spot melting or flowing of the collector tube material, a cause of failure in some high-power klystron tubes. Peak power densities per collector tube length will be on the order of those for the X-3075 klystron, a 500-kW, CW S-band amplifier (Ref. 4), and optimization of collector design will reduce peak power densities to a more conservative level (around 4 kW per square inch). Stray electrons can be prevented from impacting on the output window by using an extra crossfield magnet farther along the collector tube length. This last idea may be extended to reduce the peak power densities. A deflection coil can be designed to spread the "spent" beam symmetrically about the collector walls and over their length, as suggested by Y. Carmel and J. Nation (Ref. 5).

All of the above-mentioned potential problems appear to be solvable without recourse to completely new technology development. The only major differences between the design for the gyro-TWT amplifier detailed above and conventional klystron tubes are that the guiding magnetic field is of a larger order of magnitude than usually encountered and a magnetron-injection gun is used to form a hollow cylindrical electron beam (see Figs. 3 and 4). This latter structure is quite different from the spherical cathode, solid-beam electron guns typically used in conventional high-power linear beam tubes (Ref. 6). The magnetron-injection gun has an annular emitting surface that gives off electrons having a generally well-specified spread of perpendicular and longitudinal velocities in cylindrical coordinates. Efficiency is enhanced through use of a hollow beam since there is no RF component on the axis of symmetry (Ref. 7). (This is true for most gyrotrom devices operating near cutoff, as with the gyro-TWT being presented in this paper and the gyromonitron tube discussed in Ref. 7.)

It is therefore quite conceivable that a test or prototype gyro-TWT could be built and/or tested at a high-power tube testing site, since the beam power required is 672.40 kW CW (beam perveance is 0.50 micropervs) and there are currently available power supplies capable of delivering even greater amounts of power than this. Should such a project be undertaken at some future time and conditions for bandwidth and gain finalized, the point design presented in this paper could be scaled subsequently to meet the new conditions without any major difficulties. In such an exercise, however, it is relatively safe to assume that a crucial factor will be the cost of the superconducting magnets, whose price scales with bore length. (This is generally true in most plasma experiments using superconducting magnets.) To minimize the magnet costs, it will be necessary to increase the gain per unit length parameter from 1.14 dB/cm to something over 2.2 dB/cm. This can be accomplished at the expense of the efficiency (electronic efficiency can be expected to drop from 52.7 percent to about 20 percent), but there will be a tremendous increase in bandwidth. A −3-dB bandwidth of 3.5 GHz may be possible. Needless to say, the collector will have to dissipate tremendous amounts of power. The weight of the cooling assemblies will undoubtedly have to increase greatly and, perhaps as well, the water-pumping capacity.

However, if a more moderate design is chosen, most of the above-mentioned factors can probably be easily worked out.

IV. Summary

The gyrotron traveling wave tube amplifier presented in this article represents a not necessarily optimized point design, where considerations of maximum efficiency have been given top priority over gain per centimeter of interaction space, bandwidth, and magnet bore length factors. From the dispersion relationship, it is possible to derive the growth rate in the beam frame using convenient normalizations. Lorentz transformations yield results in the laboratory frame that can then be converted to useful design parameters. The present design can be easily scaled for differing bandwidth or gain-per-unit-length requirements, once those factors are specified.

References

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Table 1. Design parameters for a gyrotron traveling wave tube amplifier

Frequency	34.3 GHz	Guiding center radius	2.62 mm
Wave power	354.36 kW CW	Larmor radius	0.597 mm
Beam power	672.40 kW	Waveguide radius	5.46 mm
Current	9.50 A	Gain per unit length	1.146 dB/cm
Beam voltage	70.80 kV	Perpendicular electron velocity	0.401 C
Efficiency	52.7%	Parallel electron velocity	0.268 C
Magnetic field strength	13.07 kG	Beam density parameter	2.076×10^{-3}
	Conditions for maximum gain of 40 dB		
Length	34.90 cm		
Drive power	35.44 W		
−3 dB bandwidth	384 MHz (1.12%)	$c = 2.998 \times 10^{10}$ cm/sec	
−1 dB bandwidth	199 MHz (0.58%)		
	Conditions for maximum gain of 50 dB		
Length	43.63 cm		
Drive power	3.54 W		
−3 dB bandwidth	336 MHz (0.98%)		
−1 dB bandwidth	165 MHz (0.48%)		

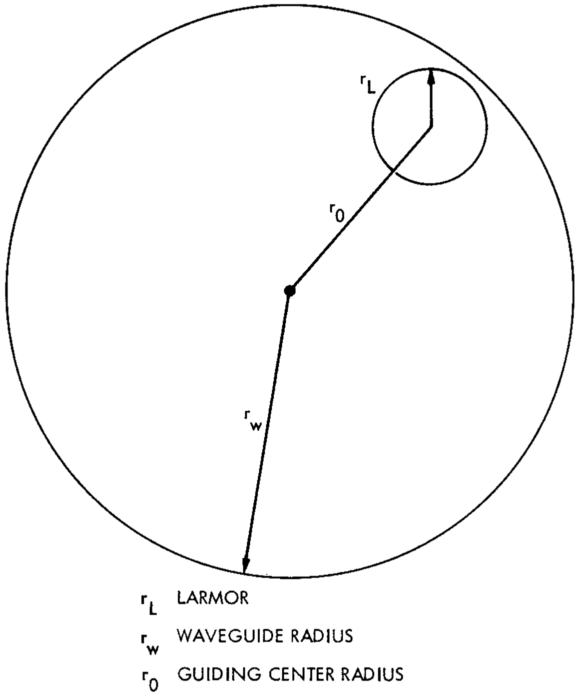

Fig. 1. Radial vectors

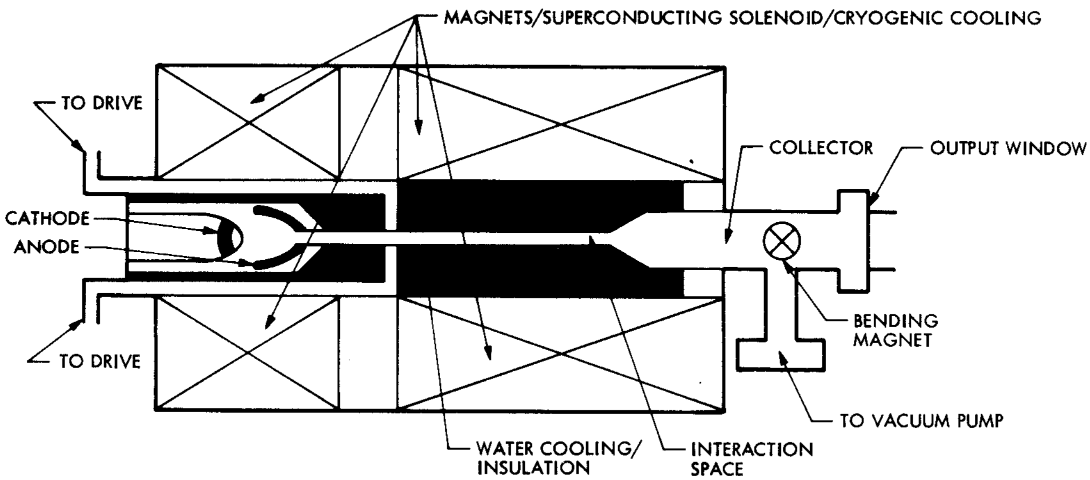

Fig. 2. Gyro-TWT amplifier

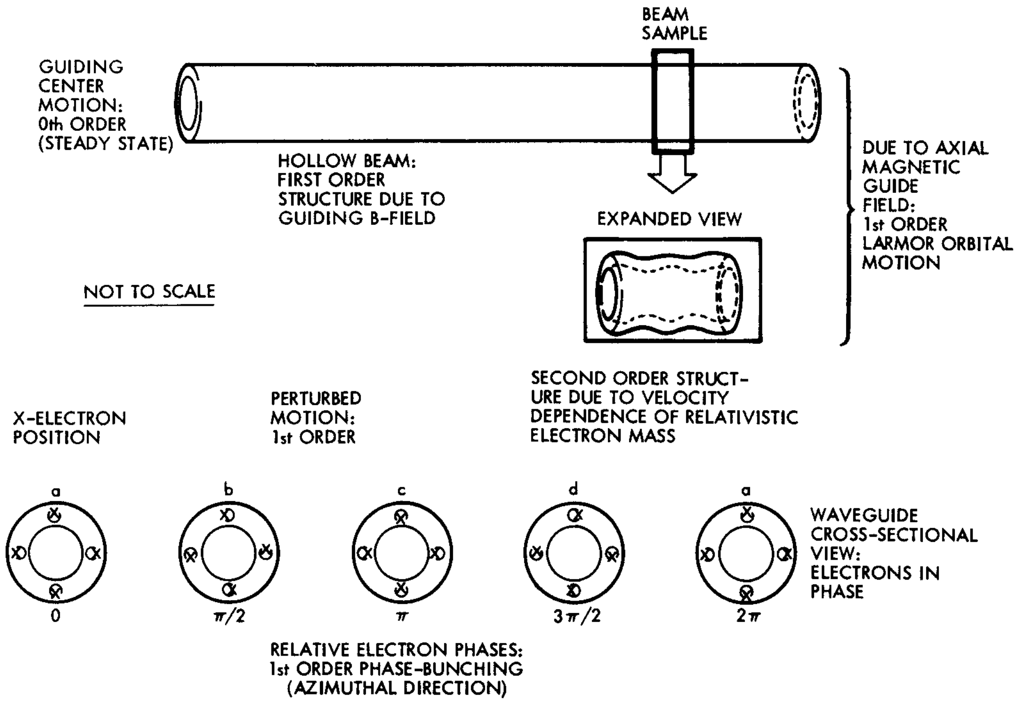

Fig. 3. The gyrotron hollow electron beam

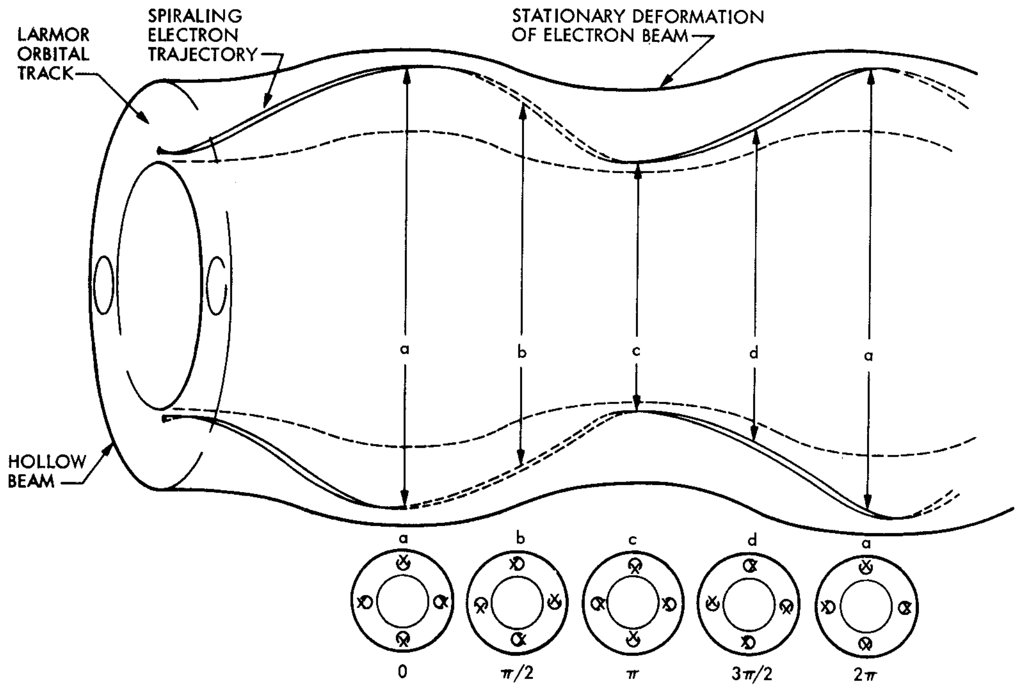

Fig. 4. Gyrotron hollow beam